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Elastic Electroadhesion with Rapid Release by Integrated Resonant Vibration

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The advancement of flexible electronic technologies (e.g. flexible chips, screens, solar panels) ^[1] has significantly increased the demand for gentle and precise manipulation of flat, thin and flexible substrates such as plastic films and sheets ^[2]. Traditional rigid robotic grippers generally have difficulty in handling flat, soft and deformable objects because of the increased mechanical and control complexity ^[3]. Soft robotic grippers have gained increasing interest due to their inherent compliance and adaptability which enable them to handle fragile objects safely ^[4]. To date, several types of soft grippers have been developed; for example, soft bending grippers using pneumatic actuation ^[5] and dielectric elastomer actuators (DEAs) ^[6, 7], jamming gripper ^[8], suction cup ^[9], gecko-adhesion ^[10] and electroadhesion ^[11]. Bending and jamming grippers are ineffective at picking-up thin, flat objects ^[8, 12]. Gecko-inspired adhesion has difficulty in grasping low surface-energy materials ^[13] (such as plastics like polypropylene) and the release of lightweight objects can also be challenging ^[3]. Suction cups can grasp flat objects but can be less effective when targeting a structured surface or porous substrate. Also, they cannot operate in a vacuum environment such as in electronic chip manufacturing ^[14]. Electroadhesion has been previously utilized to manipulate flat, flexible and lightweight substrates ^[15]. However, the slow de-adhesion (release) of lightweight substrates limits the potential applications of electroadhesion in the areas aforementioned ^[16]. Here, we developed a monolithic electroadhesive device with an integrated DEA quick-release mechanism by utilizing its resonant excitation to rapidly detach substrates from the electroadhesion pad. This

design is specialized in manipulating flexible and flat substrates with the advantages of rapid grip and release characteristics, noise-free, low energy consumption, cost-effective and easy to fabricate.

Electroadhesion (EA) is an electrically controllable adhesion between an EA pad and a substrate, subjected to a high electric field (typically in a scale of 1 MV/m). When a high voltage is applied between the electrodes of the EA pad, counter charges are induced at the surface of any object it touches, mainly due to mainly electric polarization that causes attractive forces between the object and the EA pad. This adhesion process is very fast and typically under 1s ^[17]. The slow de-adhesion phenomenon is due to the residual charge separation in the substrate after the applied voltage is removed, which diminishes slowly with dielectric relaxation ^[14]. Some solutions have been proposed to speed-up the de-adhesion process such as polarity reverse control ^[18] and using air-jets to mechanically detach the substrate ^[19]. These methods tend to increase the complexity of the gripping system and are expensive. Release by vibration has been found to be feasible and effective, as reviewed in ^[20]. An additional vibrator can be integrated with a gripper, such as piezoelectric actuators ^[21] and electrostatic actuators ^[22-23]. However, these approaches are not suitable for integration into a compliant EA pad.

DEAs are an emerging type of soft actuator which have advantages in their large actuation strains, inherent compliance, fast actuation response, self-sensing capability, large energy density and low-cost ^[24-27]. An idealised DEA consists of an elastomer membrane sandwiched between two compliant electrodes. When a voltage is applied across the electrodes, the generated Maxwell stress causes the membrane to compress in thickness and expand in area. Due to the inherent elasticity of a DEA membrane, when stimulated by an alternating voltage at a frequency close its natural frequency, its response is greatly amplified. When coupling EA with unimorph DEAs ^[3], there is potential to use DEA bending motion to detach EA pads from

the objects. However, the unimorph DEA blocking force has been found to be several orders of magnitude lower than the normal EA force ^[3] so a new DEA excitation mode must be considered.

The resonant actuation of DEAs has been adopted in applications such as loudspeakers ^[28], robotic locomotion ^[29-31] and active vibration isolation ^[32]. This technique has advantages over other vibrational actuators such as electric motors and piezoelectric actuators in terms of ease of fabrication and high deformability. For these reasons, a DEA resonator is adopted and modified as the release mechanism of our gripper. Also, the same applied voltage range for both EA and DEA (usually in the order of kilovolts) can simplify the power and control systems of this gripper.

The proposed gripper follows the typical circular DEA configuration consisting of a pre-stretched elastomer membrane bonded to a rigid circular frame and sandwiched by two circular electrodes. However, a novel advancement of our design lies in the electrodes design where one electrode is divided into two parts, EA V_+ and EA V_{GND} , as a concentric-comb EA pattern, as illustrated in **Figure 1**. The two electrodes are interdigitated near the outer edge of the membrane, while the inner region has only one electrode. The same pattern is used on the electrodes on other side of the membrane, but instead, the electrodes are all connected and are referred to as DEA V_+ . The center of the EA-DEA membrane is left electrode-free with a rigid central disk (1.4 g) bonded to the membrane. This configuration allows two actuation modes with this gripper. The first mode is EA gripping, and it is achieved by applying a voltage bias across the two EA electrodes EA V_+ and EA V_{GND} while leaving DEA V_+ off. An electric field is generated across the EA electrodes and adhesion force over the surface is exerted and flat substrates can be picked-up, as shown in **Figure 2a**. A potential drawback of EA is the residual adhesion force after removal of actuation voltage, which is due to the residual charges in the

grasped substrate. To overcome this challenge and perform fast release, the second actuation mode, DEA out-of-plane vibration, can be triggered by applying an alternating voltage to DEA V_+ and leaving EA V_+ and EA $V_{\text{GND}} = 0$. With the appropriate actuation frequency selected to achieve resonant excitation, the DEA can vibrate out-of-plane with a large amplitude and force the substrate to release. The generated EA gripping force depends on effective EA area and the magnitude of the DEA release force correlates to the DEA area. An optimal design must ensure both a sufficiently large EA area to achieve the required EA force, as well as a sufficiently large DEA area for the DEA to overcome the residual EA force for release. In this design, the EA electrodes ensures that the residual adhesion force only occurs near the outer edge of the gripper. A large central DEA electrode ensures that once the DEA mode is triggered, the central disk pushes the substrate downward to create a clear gap between the EA gripper and substrate (where residual adhesion force exists), which causes a release of the substrate, as illustrated in **Figure 2b**. The central disk helps the release process by adding mass to amplify the vibration amplitude and modifying its out-of-plane deformation profile by creating a small flat surface in the center. This ensures a complete detachment of the substrate from the EA electrodes in a direction orthogonal to the EA gripper.

For this gripper design, the speed and robustness of the release process mainly depend on the vibration amplitude of the DEA. **Figure 3a** shows the DEA stroke as a function of actuation voltage and frequency. At $V = 3.5$ kV, only the fundamental frequency stroke peak can be observed at 18 Hz. When the voltage is increased to 3.9 kV, a second harmonic occurs at ~35 Hz. The amplitude of the second peak increases significantly from 1.2 mm to 11.2 mm when the voltage is increased from 3.9 kV and it occurs at a higher frequency. As the voltage rises further, both the amplitude of the second peak and its frequency increase with a backbone curve characteristic of nonlinear dynamic systems^[33]. The out-of-plane vibration profiles of the DEA at its two peaks at $V = 6$ kV are shown in **Figure 3d-e**. The two peaks have an amplitude of

10.6 mm and 19 mm at 20 Hz and 55 Hz respectively with vibration profiles close to a conical envelope.

For lightweight objects, the adhesion period can be essentially instantaneous, so it is the releasing speed of an EA gripper that determines its performance. Here, we investigated the release period of the gripper with and without the DEA releasing mechanism for six plastic film samples with different material types and thickness (listed in supplementary **Table S1**): polyimide (PI) is commonly used in flexible circuits; polypropylene (PP), polyethylene terephthalate (Mylar), polyvinyl chloride (PVC) are largely used in packaging. Also, PP used in this work is extremely light and flexible in order to demonstrate the functionality of the developed gripper.

Figure 3f plots the measured EA-only release period (left axis) and EA+DEA release period (right axis). The raw data can be found in supplementary **Table S2**. The fastest release sample is PVC 0.2 (36 ± 9.5 secs) while the longest is PP (over 30 mins). Clearly, the long release time of all tested plastic substrates restricts the applications of EA-only grippers in lightweight material manipulations where a fast release method is required. The generation of EA force on insulating material is a result of polarization, and is strongly dependent on the substrate material type and its molecular structure ^[14]. The poor release behavior of plastic films is likely due to their relatively high molecular weight which could cause a slow dissipation of the residual charge on the substrates ^[14]. In order to investigate the effect of the EA supply voltage on de-adhesion behaviour, an AC voltage was tested (5 seconds, 3.5 kV, 30 Hz) . As shown in supplementary **Figure S2**, an AC-supply EA release is faster than an EA-only release, but with a relatively small improvement of 33% or less.

With the proposed DEA oscillation release mechanism, the release of all substrates was dramatically shortened to a scale of 100 ms, as is shown in **Figure 3f**. It can be noted that the

EA+DEA release performance of each sample shows a similar tendency to that of EA-only release, indicating that residual charges affect DEA release behavior. One reason might be that at the initial state, the flexible substrates deformed along with the vibration of gripper, then separation occurred when the residual electrostatic force declined to a threshold. With the proposed DEA release mechanism, the gripper is capable of releasing the lightest and most flexible sample (polypropylene, $m < 0.1$ g, Young's modulus ~ 1300 N/mm²) in ~ 0.5 s, compared to the extremely long release period without this release mechanism (> 30 minutes). In **Figure 3g**, we demonstrate the improvement in release speed of our EA+DEA gripper with each sample. It is worth noting that the normalized improvement does not represent the generalised performance of the device for all applications since the non-DEA release period is strongly correlated to the substrate's weight (as shown in supplementary **Figure S1**). The release behaviour is determined by the interaction of gravitational and residual EA forces, so the rapid release of relatively heavy substrates is less problematic but for lightweight substrates it is a serious limitation. It should be pointed out that the release period is also subjective to the applied electric field; in this case, an electric field of 1.75 MV/m was applied on open electrodes by considering safety factors (electrical strength of dry air is 3 MV/m).

The benefits of DEA vibration in this design can be summarised as follows: (i) actuation elements are fully integrated and centrally located into the EA pad which makes it a very compact structure that do not need an additional vibrator, which may be distally located with concomitant vibrational mode complexities; (ii) the EA gripping and DEA release mechanisms operate in the same voltage range; (iii) the developed EA-DEA is compliant; thus, reduce the damage risk to the substrates; (iv) small vibration amplitude, like piezoelectric actuators, might be less effective for flexible substrates and the DEA allows large out-of-plane deformation for release.

Limitations are acknowledged for future development. For example, the proposed EA-DEA design cannot operate in some extreme environment conditions due to the requirement for a highly elastic membrane with high dielectric constant. It should also be noted that the large vibrational amplitudes generated in the proposed design, intrinsic to its de-adhesion performance, may be unsuitable for applications where the substrate needs to be dropped from a very low height (<10 mm) since the excitation stroke could exceed this.

The excellent mechanical and electrical properties of plastic make them promising materials in flexible electronics, such as flexible chips, screens, solar panels, etc. This also necessitates a robust yet simple gripper which can manipulate flat, flexible and lightweight plastic materials. The proposed novel EA-DEA gripper shows consistent and rapid performance on different types of plastic materials in both gripping and releasing process. The adopted DEA oscillator speeds-up the release period from several minutes to 100s of milliseconds. The low-energy consumption (gripping ~ 2 mJ and releasing ~ 50 mJ), noise-free, low-cost and ease of fabrication also allow this gripper to be a promising candidate for industrial applications in the future.

Experimental Section

Fabrication: For the DEA membrane, an elastomer membrane, Elastosil (thickness 100 μm , Wacker Chemie AG), was adopted in this work. The elastomer was biaxially pre-stretched by 1.2×1.2 and bonded to a circular frame using silicone transfer tape (ARclear 93495, Adhesives Research). In this work, EA electrodes were made of conductive rubber which was formed of a mixture of 5 wt.% carbon black (VXC72R, Cabot) and silicone with a mixer (WZ-50006-01, Cole-Parmer), then casted on a laser engraved acrylic template, and finally crosslinked at 40°C in an oven for 12 hrs after mixing. Then, a thin layer of silicone was spin-coated on the electrode to help the release of the electrode from the cast mould. To minimize the effect of the

electrodes on increasing the stiffness of the elastomer, a low modulus elastomer (Ecoflex-20, Smooth-on Inc) was adopted. The fabricated electrode has a thickness of ~0.2 mm. Then the electrode was bonded to the elastomer membrane by a thin layer of spin-coated Ecoflex-20 and then crosslinked at 40°C in the oven for an hour. As the electrode on the other side of the elastomer will not contact with the substrate, it is made by pad-printing carbon conductive grease (MG Chemicals). To avoid inherently sticky behaviour due to surface tackiness, the EA pad's contact surface was coated with talcum powder.

Characterization of Stroke as a Function of Actuation Voltage and Frequency: To characterize the relationship between the vibration amplitude and its actuation voltage amplitude and frequency, square wave frequency sweeps were conducted with five different voltage amplitudes of 3.5 kV, 3.9 kV, 3.95 kV, 5 kV and 6 kV (electric field $E = 50.4, 56.2, 56.9, 72,$ and $86 \text{ V}/\mu\text{m}$). Actuation frequency ranged from 1 to 60 Hz with an increment of 1 Hz. The actuation voltage wave was generated by MATLAB (Mathworks) and amplified by a high voltage amplifier (Ultravolt 5HV23-BP1). The displacement of the DEA was measured by a laser displacement sensor (LK-G152 and LKGD500, Keyence). A data acquisition system (National Instruments, BNC-2111) was used for signal communication between sensor and amplifier and the PC.

Measurement of Release Period: As introduced in the supplementary **Video S1**, the gripper first approached the target plastic film with a 0.5 to 1 mm gap. Then, 3.5 kV was applied to the EA pad. After charging the EA pad for 10 seconds to ensure steady-state gripping, the gripper was lifted. Release period recording was initiated when switching off the employed EA and was accomplished when substrates completely detached from the gripper. The whole process was recorded with a 60 frame per second Panasonic DMC-G80 camera (Panasonic UK). We

repeated all experiments three times and recorded temperature and humidity, which showed negligible variance (temperature = $23.67 \pm 0.47^{\circ}\text{C}$; humidity = $42.67 \pm 1.25\%$).

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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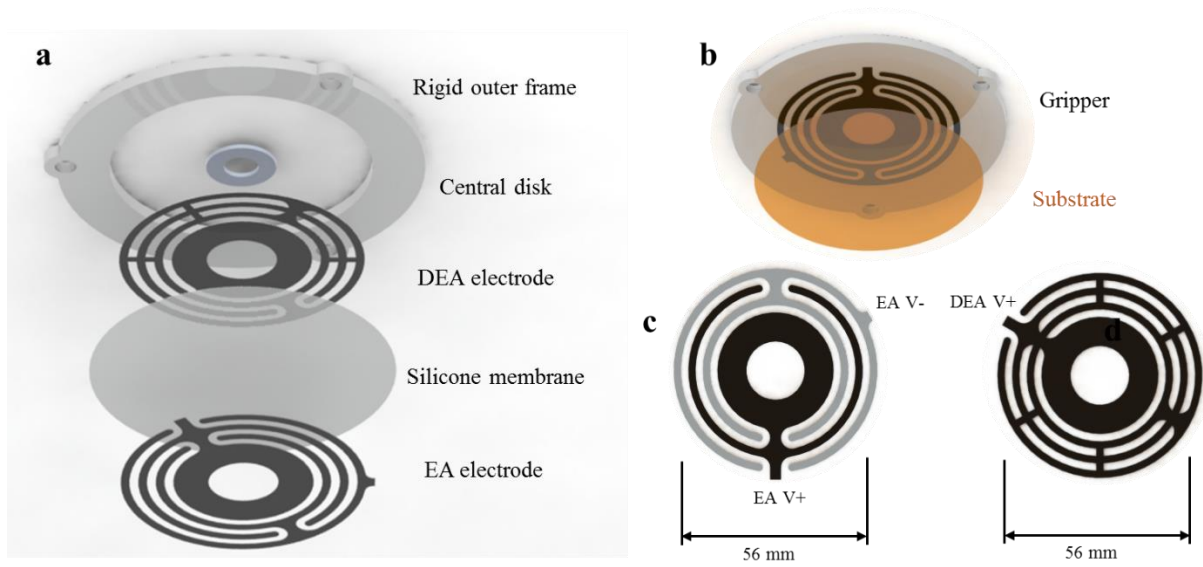


Figure 1. Structure of the EA-DEA soft gripper. (a) The gripper consists of a pre-stretched elastomer membrane bonded to a circular frame. Two EA electrodes and one DEA electrode are attached to two sides of the elastomer. A rigid disk is placed in the center of the membrane. (b) A view of the gripper approaching to a substrate. The gripper has an effective EA diameter of 56 mm and the gripper has an outer diameter of 80 mm. (c) EA electrodes design. (d) DEA electrode design.

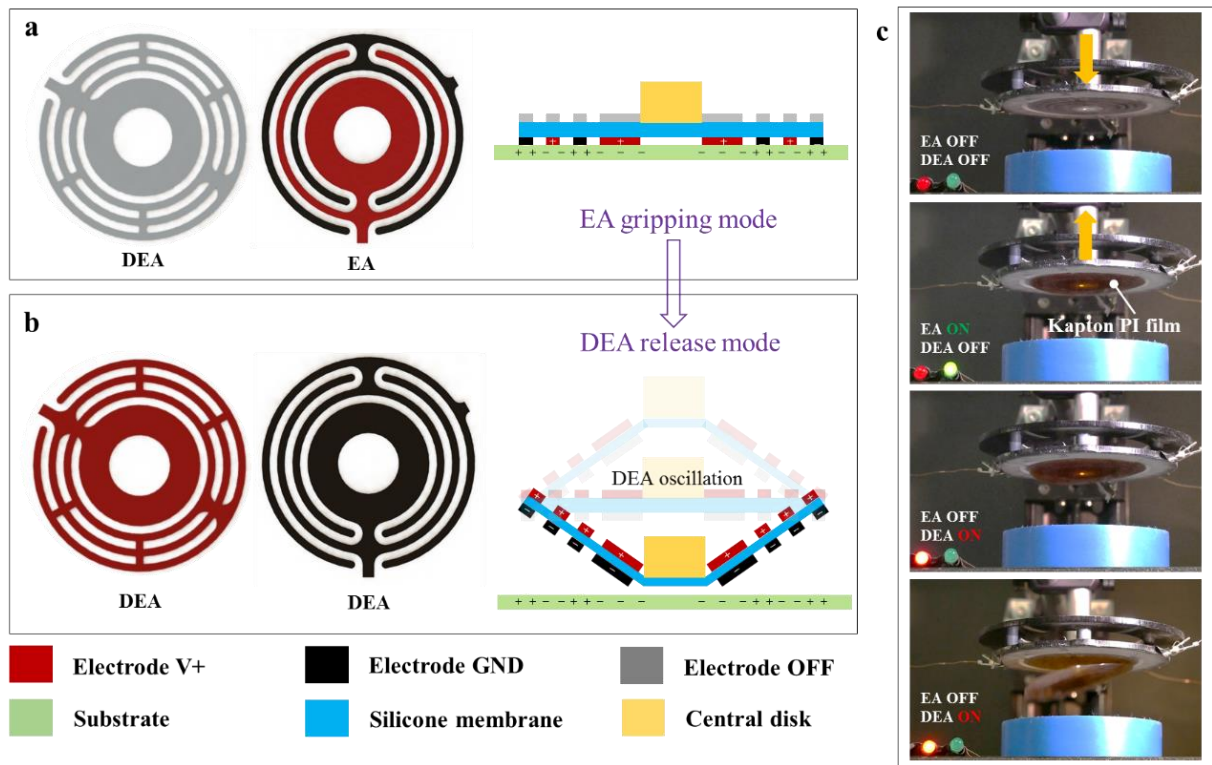


Figure 2. Illustration of the two actuation modes of this gripper: EA gripping mode and DEA oscillation release mode. (a) EA gripping mode: A voltage bias is applied across the two EA electrodes while leaving DEA OFF. Electric field is generated and homogeneous adhesion force over the surface is exerted and flat substrates can be grasped. (b) DEA release mode: An alternating voltage is applied across the electrodes. The out-of-plane oscillation of the DEA causes the release of the substrate. (c) Picking up and releasing a piece of Kapton film. The gripper is first moved downward to allow contact with the substrate. Then EA is turned on and the substrate is lifted. To release the substrate, EA is switched off and DEA is turned on. The vibration of the DEA causes the release of the substrate in less than 0.5 s.

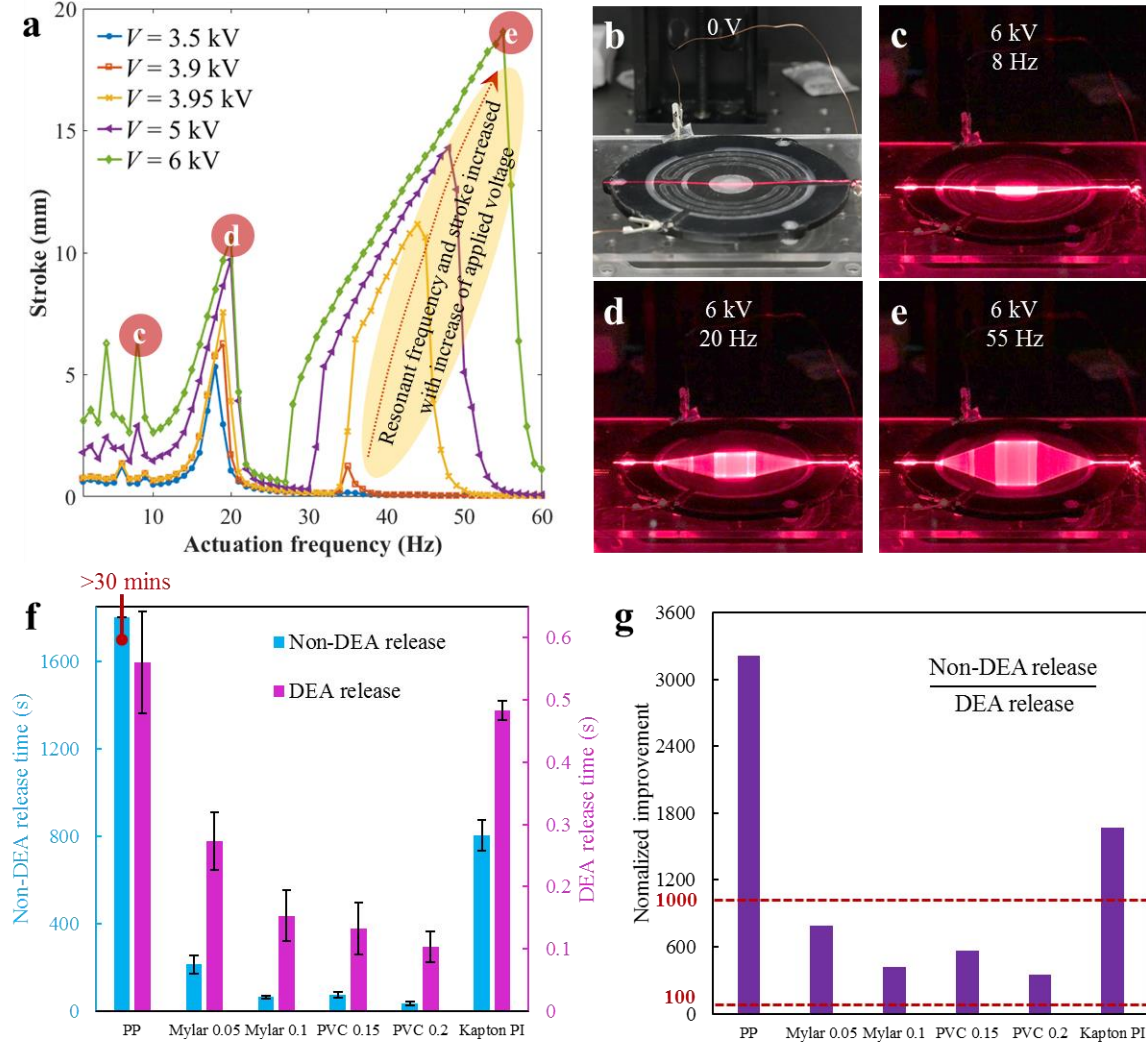


Figure 3. Performance investigation of the developed EA-DEA gripper. (a) Square wave frequency sweeps from 1 to 60 Hz with five different voltage amplitudes of 3.5 kV, 3.9 kV, 3.95 kV, 5 kV and 6 kV. (b) Experimental setup for visual realization of the DEA oscillation geometry profiles, where a laser pointer was placed above the gripper. (c) Oscillation geometry profile at 8 Hz. (d) Oscillation geometry profile at 20 Hz. (e) Oscillation geometry profile at 55 Hz. (f) Release period without DEA oscillator (blue, left axis) and with DEA (purple, right axis) for six samples. (g) Normalized improvement of non-DEA release over DEA release demonstrates it minimized the release period by at least two orders of magnitude.